Modeling and Processing for Vector Sensors

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LONG-TERM GOALS

Using recently developed sensor technology, the long-term goals are to understand how pressure and particle velocity interact and propagate in the ocean waveguide, and to develop ideas for future naval systems that benefit from this technology.

OBJECTIVES

The objectives of this work are: to develop models and processing techniques for acoustic vector sensors, to collect data at sea during the Makai Experiment (at Kauai's PMRF in September '05), and to demonstrate processing capabilities that exploit the unique characteristics of vector sensors.

APPROACH

We have collected data at-sea during the Makai experiment in September 2005, using a 5-element array of Wilcoxon TV-001 vector sensors, borrowed from Jerry Tarasek at NSWC-Carderock.

Our approach for modeling vector sensors will be to initially use normal modes for low frequencies and Gaussian beams for mid to high frequencies, basically piggy-backing upon existing models to calculate pressure at a set of points from which the various pressure derivatives can be calculated (i.e. a finite difference approximation). We plan to compare our models with the data we have recorded at sea.

In addition to using the collected data to validate our models, we plan to assess improvements afforded by vector sensors in broadband model-based tracking, acoustic communications, and using ambient noise to image the seafloor sediment layers.

WORK COMPLETED

Modeling

Developed normal mode and Gaussian beam models for predicting particle velocity in an underwater waveguide. Benchmarked these results against the OASYS wavenumber integral model. These three models are producing consistent predictions in the simple cases in which they were compared.

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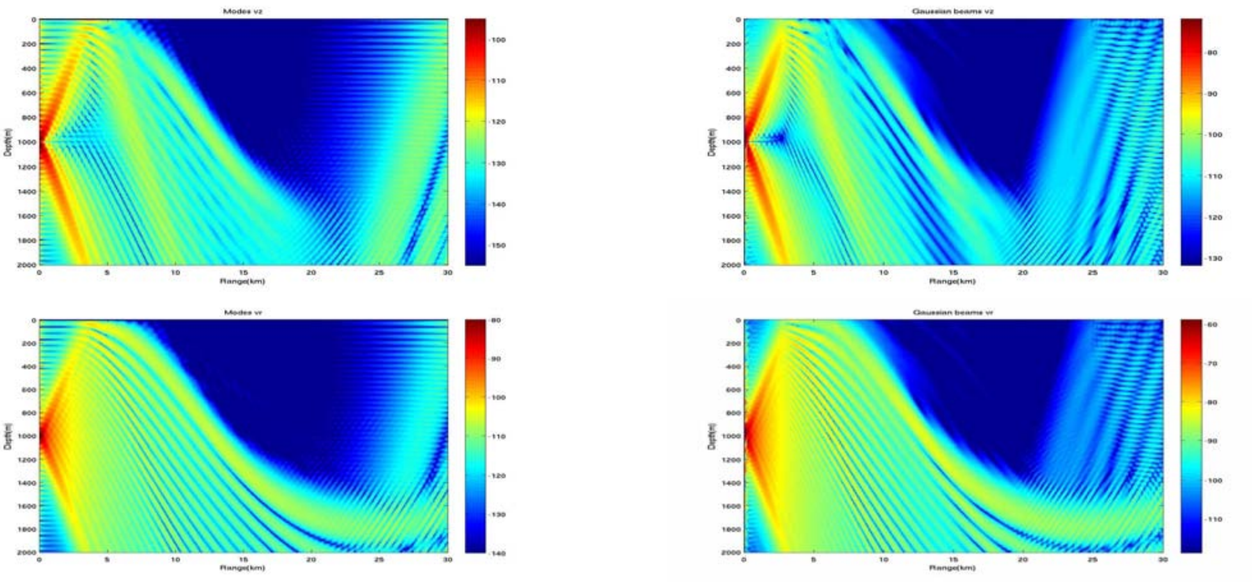

Figure 1. Modeling z-component or vertical particle velocity (top row) and r-component or horizontal particle velocity (bottom row) using normal modes (left column) and Gaussian beams (right column). The Bellhop model was modified to incorporate particle velocity. Using normal modes, analytical expressions for the partial derivatives of the modal expansion for the pressure were derived in terms of the depth derivatives of the mode shapes, in addition to the mode shapes and wavenumbers used for calculating the pressure alone. The depth derivatives of the modes were numerically approximated by finite differences.

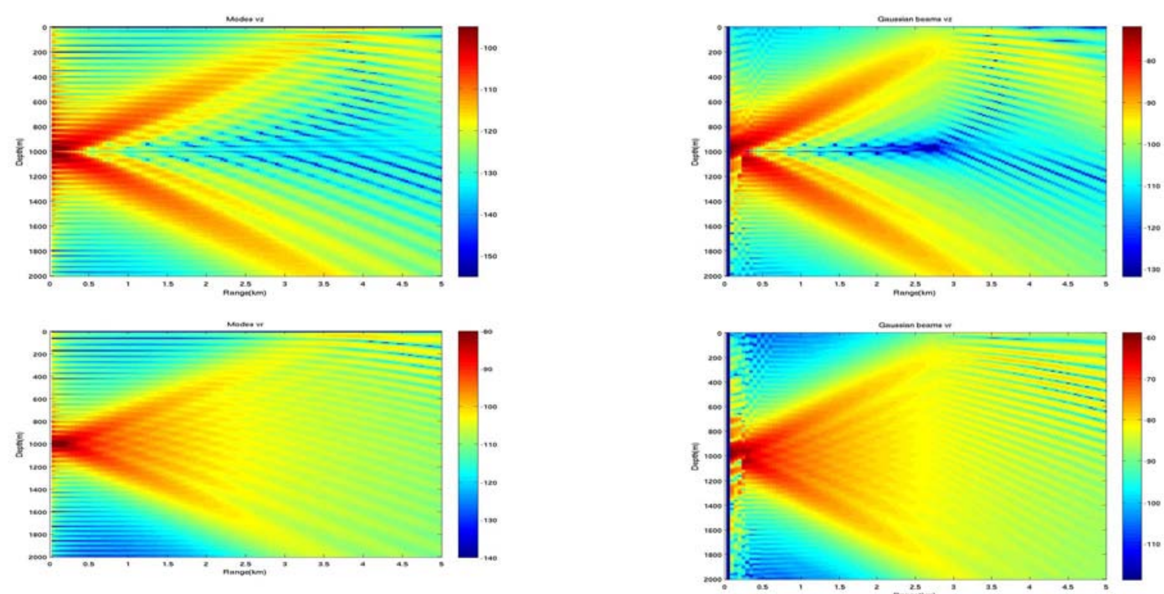

Figure 2. Blowup of Figure 1 around the source, showing the details of the normal mode and Gaussian beam modeling results for the two components of particle velocity (vertical component in top row, horizontal component in bottom row).

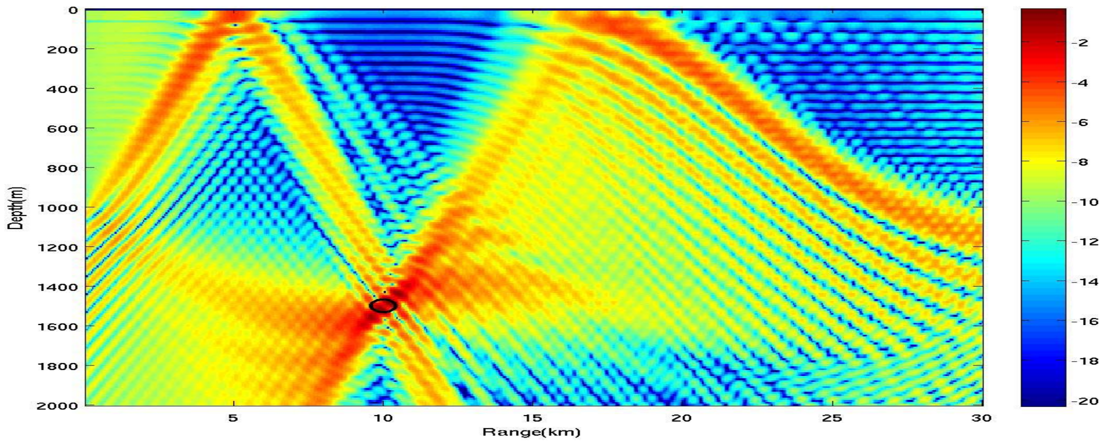

Figure 3. Simulated MFP result, using Gaussian beams to produce "data", and normal modes for "replica". This is a test of consistency between the two models. All three components were matched, pressure, vertical particle velocity and horizontal particle velocity.

Makai experiment: using NSWC-Carderock 5-element vector sensor array (TV0001-series elements)

In a collaborative effort with Bruce Abraham (of Applied Physical Sciences), participated in Makai Experiment in September 2005. Performed calibration of NSWC 5-element vector sensor array at the SPAWAR Space and Naval Warfare Systems Center's TRANSDEC test facility. Deployed NSWC array numerous times during Makai Experiment, recording several days worth of data, including ambient noise, channel probes in low, mid and high frequency bands, acoustic communications waveforms, and marine mammals.

During the Makai experiment, the array was deployed five times:

1. Fixed-fixed acoustic communications (8-14 kHz band) on 9/21/2005.
2. Fixed-fixed acoustic communications (8-14 kHz band) on 9/23/2005.
3. Brief mini-calibration off the stern on 9/24/2005.
4. Field-calibration experiment with a towed source on 9/25/2005 (850-1250 Hz, 1-9 kHz, and 8-14 kHz bands).
5. Ambient noise measurements on 9/26/2005.

The acomms band is well above the design frequency of the array, so it is not clear what will come of the acomms packets, but these deployments contain other interesting data. For example, there are many dolphin whistles during the 9/23 deployment, so we plan to test whether the vector sensor array can be used to null out the ship from which the array is deployed, while simultaneously tracking these dolphin sources of opportunity.

The Field-calibration experiment provided probably the most promising data for testing source tracking (in low and mid frequency bands) and acomms spatial processing (mid band packets were

transmitted). This deployment also included a 24-element hydrophone array, enabling comparisons between the 5-element vector sensor array and a comparable hydrophone array. Figure 1 shows the configuration and measured impulse response during this deployment.

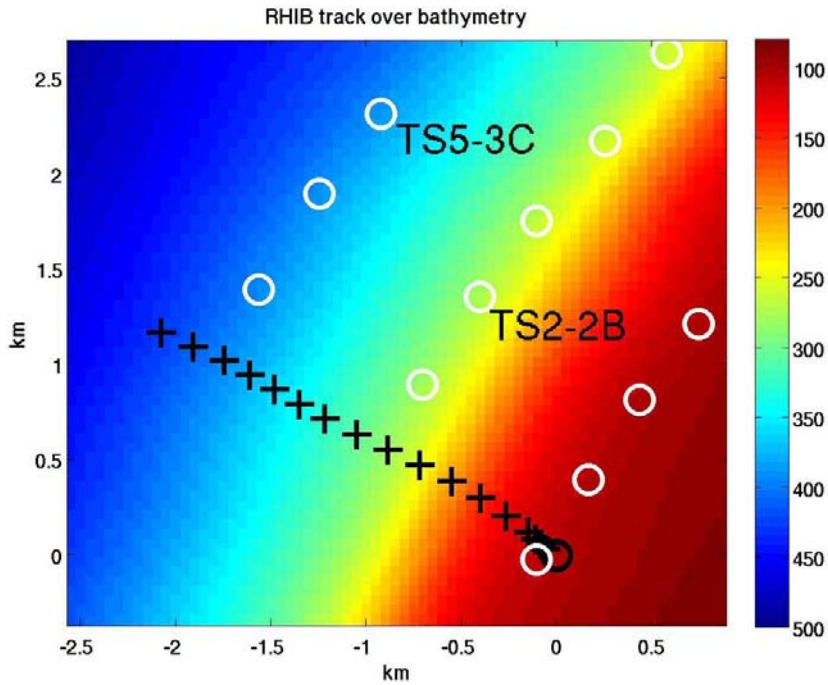

Figure 4. Makai field calibration experiment configuration. Lubell 916 underwater speaker was towed by a RHIB (plus marks), starting at a range of 2.3 km where ocean was 450 meters deep and transiting toward research vessel Kilo Moana (the black circle at the origin). The white circles indicate the experiment waypoints. Two of these waypoints were occupied by thermistor strings named TS5-3C and TS2-2B.

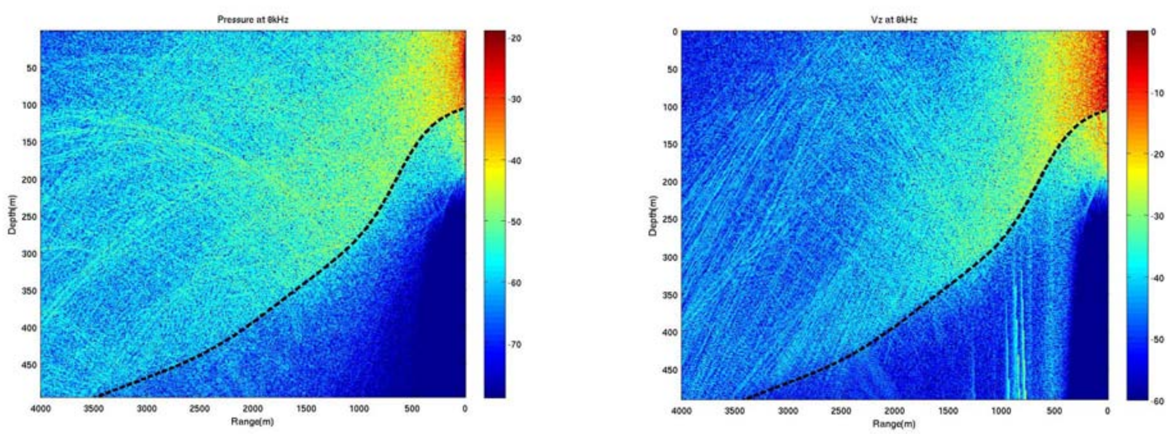

Figure 5. TL plots at 8 kHz calculated by Bellhop Gaussian beam model for range-dependent propagation during Makai Field Calibration experiment. Left figure shows pressure and right figure shows vertical particle velocity.

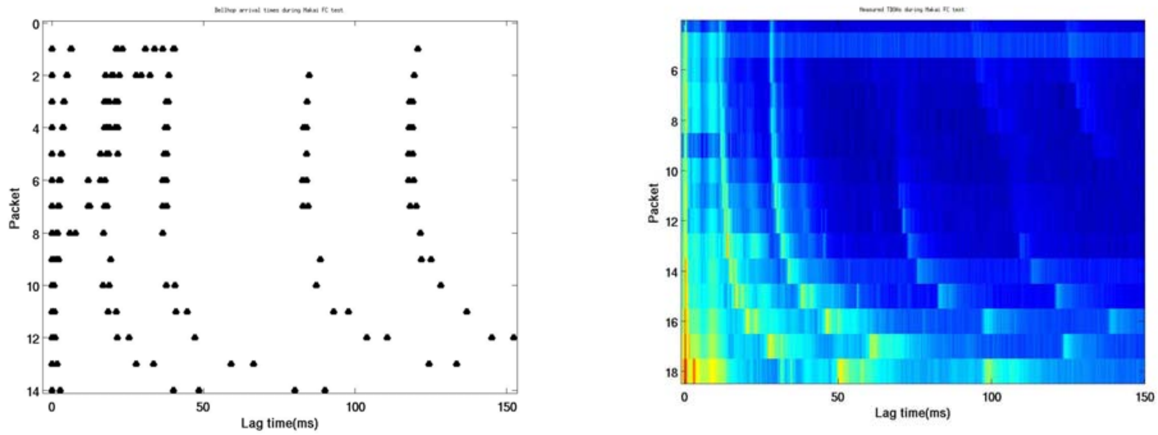

Figure 6. Time Differences Of Arrival (TDOAs) at each packet, modeled by Bellhop Gaussian beam model for range-dependent Makai Field Calibration experiment configuration (left figure). In figure at right, measured impulse response function at each packet - compare to TDOAs in previous figure. The waveform in each scan is the incoherently averaged matched filter output envelope, calculated from 30 LFM chirps, each chirp having duration 50 ms, sweeping from 8-14 kHz, with a pulse repetition interval of 200 ms. The probe signals were transmitted from a Lubell 916 underwater speaker at a depth of 10 meters deployed from a Rigid Hulled Inflatable Boat (RHIB) at ranges starting at 2.3 km at the start of the experiment and ending less than 200 m from the research vessel Kilo Moana, from which the NSWC vector sensor array was deployed. These impulse response measurements were made from a single pressure phone of the first element of the 5-element array.

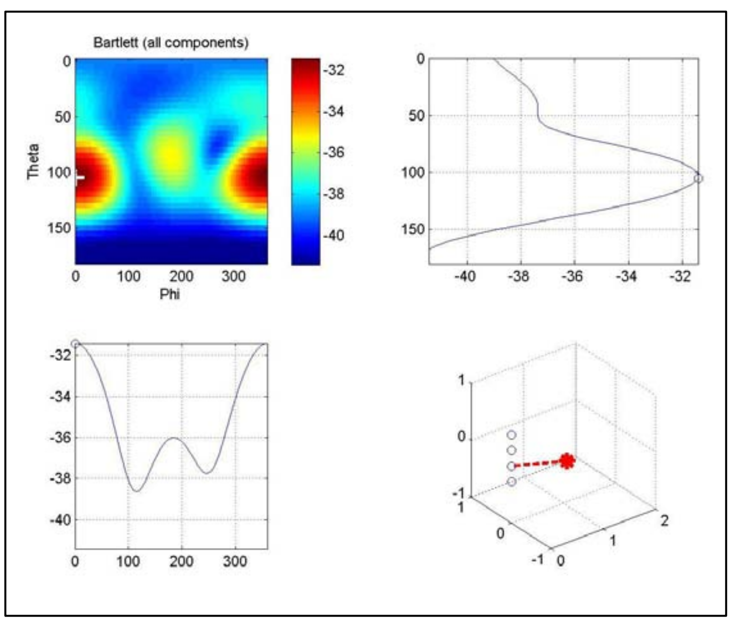

Figure 7. Beamforming using pressure and all three particle velocity components at each of 4 vector sensors at 4 kHz (during towed source transmissions). Upper left plot shows how power is distributed in elevation and azimuth. Adjacent figures (upper right and lower left) show slices through 2D beam pattern that intersect the global peak. Lower right plot shows array and direction of signal.

Using vector sensor arrays for ambient noise imaging – small, sparse or towed configurations

Working with Martin Siderius, using a combination of simulated and real data from the Makai experiment, demonstrated how vector sensor arrays can be used in a towed array configuration to exploit ambient noise for imaging the layer structure in the bottom.

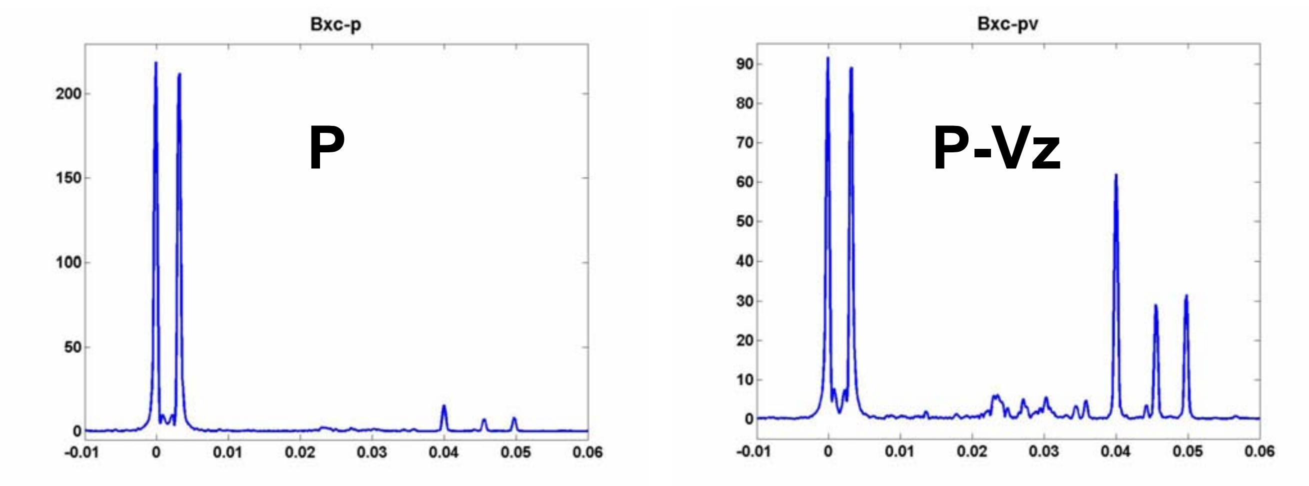

Figure 8. Comparison in simulation of pressure and vector sensor arrays (16-element arrays) for using beamforming to isolate surface from bottom-reflected ambient noise and image the ocean bottom layer structure. The peaks at the origin correspond to the ambient noise waveform crossing the array. The peaks between .04 and .05 (seconds) correspond to the reflections from three sediment layer boundaries in the ocean bottom. The ambient noise module (OASN) from the OASES wavenumber integral model was used to synthesize the surface-generated noise. Because the combination of the pressure and vertical particle velocity can form a cardioid response with a deep null in a direction 180 degrees offset from the look direction, the vector sensor array shows dramatically improved capability to recover the bottom layer structure. OASES was run for frequencies spaced every 4 Hz from 500-4000 Hz. The correlation of the up and down beams is performed in the frequency domain and the cross-correlation waveform shown in the figures is synthesized using an inverse FFT. The resolved three peaks between .04 and .05 correspond perfectly with the bottom layers specified as an input to the OASN model in the synthesis of the ambient noise.

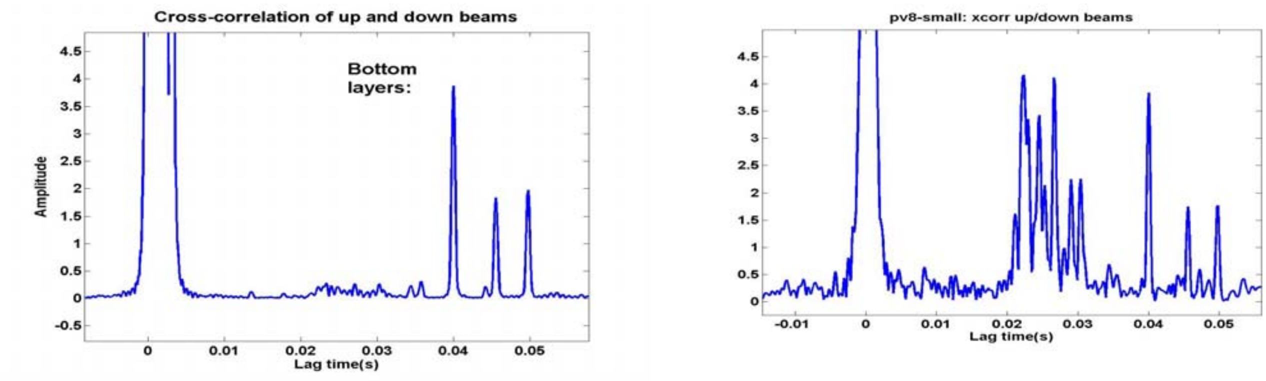

Figure 9. Left figure shows results using a sparse subset of the original 16-element vertical line array of vector sensors (4 elements from the original 16 are used here, but spanning the original aperture). Right figure shows results using a short subset (the first 4 elements of the array are used). In these cases, vertical line arrays are used. In the short array configuration (right figure), the arrivals between .02 and .03 (seconds) are believed to be two arrivals of the head wave coming from the bottom at the critical angle. The long array produces narrow enough beams that the head wave arrival does not show up. The short array has very fat beams, so the head wave leaks into the up and down beams being used.

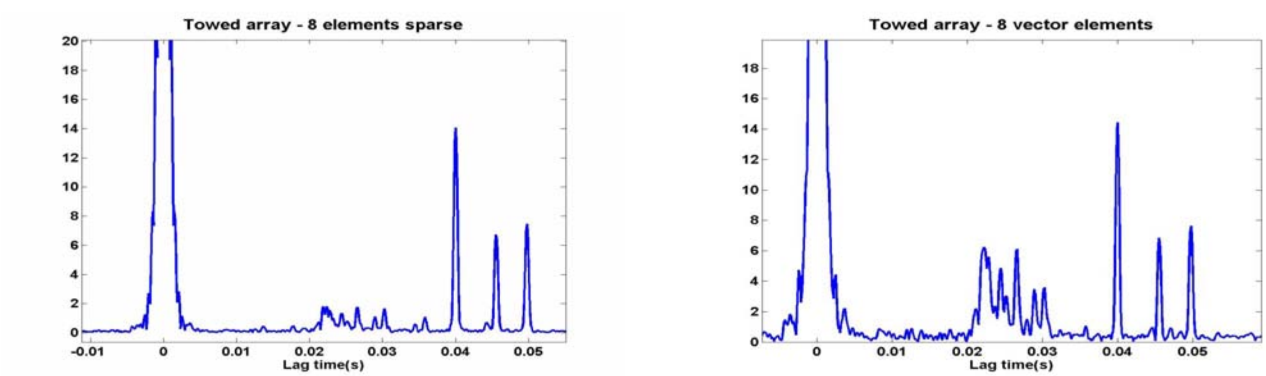

Figure 10. These results show that a horizontal line array (e.g. a towed array) will work as well. The left figure shows a sparse subset of 4 elements, spanning the original aperture. The right figure shows a short 4-element subset (of the original 16 elements). Here too we see the leakage of the head wave (irregular arrivals between .02 and .03 seconds), in the short array and muvh less so in the sparse long array.

ISSUES

Prior to the Makai experiment, the vector sensor array was calibrated at SPAWAR's TRANSDEC test facility in San Diego. However, upon unpacking the array, we found that the foam sleeve in which the sensors were embedded was saturated with air bubbles. The array was suspended vertically in the tank overnight, in the hope that the bubbles would migrate to the top of the array, but the measurements made on the second day remain suspect. The array was shipped to Wilcoxon in the time remaining before the Makai experiment, where it was re-pressurized and refilled with ISOPAR. It is not yet clear how this refurbishing impacted the array calibration.

RESULTS

Numerical acoustic propagation models based on normal modes and Gaussian beams were extended to handle particle velocity sensors. In particular, I developed a post-processor for Michael Porter's Kraken normal mode model (that calculated particle velocity) and Michael Porter (ONR's High Frequency Initiative) modified his Bellhop Gaussian beam model to calculate particle velocity. I did some preliminary benchmarking of these extensions, comparing Bellhop particle velocities to Henrik Schmidt's OASES wavenumber integration model and to my normal mode based particle velocities.
I worked with Bruce Abraham (of Applied Physical Sciences) to deploy a 5-element vector sensor array (on loan from Jerry Tarasek of NSWC Carderock Division) during the Makai experiment off the coast of Kauai in Fall 2005. We also made some detailed measurements on this array at the TRANSDEC test facility in San Diego, CA, with the help of Keyko McDonald. I have been testing a number of algorithms on this data, including own ship cancellation and a number of beamforming configurations.

Modeling and work with my experimental data confirm that:

- Vector sensor arrays remove ambiguities in "degenerate" array configurations (e.g. left-right ambiguity of line arrays and planar arrays)
- Vector sensor arrays remain effective in sparse or compact configurations

I worked with Martin Siderius to explore how vector sensors could be used to directly measure the ocean bottom sediment layers using surface ambient noise as a probe source. In this application, an array of pressure sensors must be deployed vertically in a stationary or slowly drifting posture. We have shown in simulation that a vector sensor array may be able to do the same job in a towed array configuration, thus enabling the bottom to be mapped while the platform I underway. We are hoping to demonstrate this experimentally in the near future.

Gerald D'Spain and I organized a special session on vector sensor modeling and processing at the 152nd Acoustical Society of America in Providence, Rhode Island, in June 2006.

IMPACT/APPLICATIONS

Vector sensors provide greater flexibility (than pressure sensors alone) in designing array configurations for a variety of US Navy applications, including source tracking, environmental measurements and communications. In particular, their ability to provide performance in compact and

degenerate configurations (i.e. in linear or planar arrays), may make them especially well-suited to be deployed from robotic vehicles like AUVs and gliders.

RELATED PROJECTS

My work on vector sensors is connected to other programs, such as PLUSNet (we are planning to use some of the vector sensor array data recorded during the MB06 experiment to test the algorithms being developed in this project), ONR's High Frequency Initiative (I have been working with Michael B. Porter to modify existing propagation models to make predictions for vector sensors), and an ONR program on geoacoustic inversion (I have been working with Martin Siderius on using ambient noise to image the ocean bottom).

In the following year, I will be working on underwater acoustic communications using MIMO configurations (in an ONR-funded Phase II STTR program with Prof. Tolga Duman of Arizona State University and Geoff Edelson of BAE Systems) and also ONR's SignalEx program, at which time I hope to explore potential benefits of using vector sensors in communications receivers.

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